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Modeling the effects of nuclear fuel reservoir operation in a competitive electricity market.

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Abstract

In many countries, the electricity systems are quitting the vertically integrated monopoly organization for an operation framed by competitive markets. In such a competitive regime one can ask what the optimal operation/management of the nuclear generation set is. We place ourselves in a medium-term horizon of the management in order to take into account the seasonal variation of the demand level between winter (high demand) and summer (low demand). A flexible nuclear set is operated to follow a part of the demand variations. In this context, nuclear fuel stock can be analyzed like a reservoir since nuclear plants stop periodically (every 12 or 18 months) to reload their fuel. The operation of the reservoir allows different profiles of nuclear fuel uses during the different seasons of the year. We analyze it within a general deterministic dynamic framework with two types of generation: nuclear and non-nuclear thermal. We study the optimal management of the production in a perfectly competitive market. Then, we build a very simple numerical model ((based on data from the French market) with nuclear plants being not operated strictly as base load power plants but within a flexible dispatch frame (like the French nuclear set).

Our simulations explain why we must anticipate future demand to manage the current production of the nuclear set (myopia can not be total). Moreover, it is necessary in order to ensure the equilibrium supply–demand, to take into account the non-nuclear thermal capacities in the management of the nuclear set. They also suggest that non-nuclear thermal may remain marginal during most of the year including the months of low demand.

Key words: Nuclear technology, non-nuclear thermal technology, electricity, nuclear fuel "reservoir", perfect competition, merit order, follow-up of load, seasonal demand.

JEL code numbers: C61, C63, D24, D41, L11.

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Résumé

Dans de nombreux pays, les systèmes d'électricité sont en train de quitter l'organisation de monopole verticalement intégré pour une opération encadrée par des marchés concurrentiels. Dans un tel régime concurrentiel, on peut se demander ce qu'est l'opération/la gestion optimale du parc de génération nucléaire. On se place dans un horizon "moyen terme" de la gestion afin de prendre en compte les variations saisonnières du niveau de demande entre l'hiver (forte demande) et l'été (basse demande). Un parc nucléaire flexible permet de suivre une partie des variations de la demande. Dans ce cadre, le stock de combustible nucléaire peut être analysé comme un réservoir puisque les centrales nucléaires s'arrêtent périodiquement (tous les 12 ou 18 mois) pour recharger leur combustible. La gestion de ce réservoir permet de profils différents d'usages de combustible nucléaire au cours des différentes saisons de l'année. On se place dans un cadre dynamique déterministe général avec deux type de génération : nucléaire et thermique non-nucléaire. Nous étudions la gestion optimale de la production dans un marché parfaitement concurrentiel. Ensuite, nous construisons un modèle numérique très simple (basé sur les données du marché français) où les centrales nucléaires ne sont pas opérées à production constante, mais dans un cadre de placement flexible (comme le parc nucléaire français).

Nos simulations expliquent pourquoi il faut anticiper la demande future pour gérer la production actuelle du parc nucléaire (la myopie ne saurait être totale). Il faut de plus pour assurer l'équilibre offre–demande prendre en compte les capacités thermiques non nucléaires dans la gestion du parc nucléaire. Elles suggèrent que le thermique non-nucléaire peut rester marginal pendant la majeure partie de l'année, y compris durant les mois de basse demande.

Mots clés : Technologie nucléaire, technologie thermique non-nucléaire, électricité, "réservoir" de combustible nucléaire, compétition parfaite, merit order, suivi de charge, demande saisonnière.

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1 Introduction

The nuclear generation technology is mainly differentiated from other generation technologies by its very high fixed cost and relatively low marginal cost. Consequently, nuclear is used to serve base load: targeting a given and constant minimum demand. In the past, in an integrated monopoly regime, nuclear could "easily" be operated at its maximum capacity; and this did help to cover its fixed costs (e. g. United Kingdom, see Ref. [8]). However in numerous countries, electricity systems are passing from monopoly to a frame of competitive markets (e. g. European Union) which reopens -both empirically and theoretically- the question of nuclear operation.

Economic reasoning supports that in a changing environment for the production process, the choice and operation of generation technology should also change. It therefore questions how nuclear plants should be operated in an open market frame. What could be the optimal management of a nuclear set in a competitive setting? Within this new competitive framework, we assume that we have to distinguish two time horizons of operation: the short-term and the medium-term.

The short-term operation of plants is related to daily variations of demand. The core point here is the daily to intra-daily flexibility of nuclear generation. Can the plant manager adjust daily or intra-daily its power to follow the demand in order to maximize its "costs versus revenue" margin. Of course the nuclear output flexibility is constrained by the generation ramping rate that bounds the variation of the output between two steady production periods. The short-term horizon is therefore organized around a "hard" technological constraint: the inherent operational flexibility of a given nuclear plant technology. Different nuclear technologies have different operational flexibilities. In France that short-term flexibility is quite high for a nuclear set.

However we do believe that the second time horizon - the medium - deserves at least the same or even more attention than short-term. While the short-term horizon is caped by a straight technological constraint (the operational flexibility of nuclear output), the medium-term horizon appears to be a "pure" economic strategy question. In the medium-term, the nuclear manager has to set his seasonal variation of output according to his forecast of demand level. We emphasize only two stylized seasons: a "winter" season (with high demand) and a "summer" season (with low demand). In this medium-term horizon, a core feature is that nuclear fuel appears to be a "reservoir" of energy - partly similar to a water reservoir of energy. Thus, we will look at this question as a rational economic analysis of the operation of a nuclear fuel "reservoir". The nuclear manager is allocating a limited and exhaustible amount of nuclear fuel between the different seasons having different demands and pricing features. The characteristic of nuclear as a reservoir is based on the discontinuous reloading of the nuclear reactor. Nuclear plants stop only periodically (from 12 to 18 months) to reload their fuel. Then managers have to decide what the expected and current length of each "campaign of production" is; as the final amount and current temporal profile of fuel uses.

To build the corresponding modelling, we aim at establishing a microeconomic model of operation of nuclear power stations in a flexible market based operation framework. We absolutely do not claim that the French nuclear producer did or is doing what we are modelling. We only treat academically a hypothetical case while borrowing some key features from the existing world. The French nuclear set is of course very appealing for us: because of the nuclear importance (80% of the French electricity production being nuclear); because the French nuclear set does not entirely operate as base load and has developed a unique load-following management to partly respond to the daily and seasonal variations of demand; because of the particular geographical position of France connected to six different countries and to the core of continental Europe; also, to end, because the existing economic literature on this precise topic is more than extremely reduced and close to a vacuum.

Assuming that nuclear plants and hydro storage plants have in common a few similar reservoir characteristics, despite their strong operational differences, we start in section 2 with an analysis of nuclear fuel as "reservoir". In section 3, we build a model to study the operation of "market based" nuclear reservoirs in a perfect competitive setting. This model can be used like a benchmark to trace and measure a hypothetical market power exercised by nuclear producers (See Smeers (2007)). In section 4, we collect some basic data to feed our model. In section 5, we run numerical tests of our model with that set of data. Section 6 concludes.

2 Medium-term aspect: The characteristic of the nuclear fuel "reservoir".

There are few theoretical analyses of the operation of nuclear plants in a competitive market while the difficulties of that modelling are numerous. It is obvious that gas or coal power stations operate a load follow-up, which implies a variable fuel consumption and supply. This is not the case with nuclear power. The existing economics of nuclear estimate that nuclear plants should run all the year at the maximum of their capacity to cover their extremely high fixed costs. Such nuclear plants in a competitive market should roughly be price-taker. This is why nuclear technology is assumed to resemble to the hydro run-of-river because the latter does not try to make any follow-up of load. In the French case, nuclear generation is not of that kind (see Ref. [15]) France is distinct from other countries like UK or Sweden because its far higher generation of nuclear power implies not to run nuclear plants strictly as rigid base load units. In the French case the similarity between hydro and nuclear would spontaneously be that both are reservoirs.

From a technical point of view, the heart of a French-like nuclear reactor consists in a bunch of nuclear fuel bars controlled through neutralizing graphite bars moving under control from outside. These reactors stop periodically to reload their fuel and neutralizing bars after the opening of the heart of the reactor. After this reloading a new period (named "campaign") of production starts. A campaign consists in transforming the potential energy contained in the uranium bars into electricity (it takes between 12 and 18 months generally). The regular length of a campaign depends on many factors (technical specificities of the reactor, size, age, management decision to reload the reactor's heart per third or quarter of its full capacity, type of nuclear fuel put into the fuel bars, forecasted average rate of use of the reactor, regulatory constraints issued by safety inspectors...) (see Ref. [11], [18], [19], [20])

Reloading of reactors is to be avoided when the level of demand is high (which is winter in France). For operational reasons, the normal duration of a campaign is determined in advance to get a general scheduling of reloading. That action requires the intervention of many qualified persons external to the nuclear operator. It also has to be consistent with the scheduling of all the 58 reactors of the French set. As a result the manager of a nuclear plant has a given horizon in which to manage the fuel stock. However the exact duration of each plant campaign can be shortened or expanded at the request of the general nuclear set manager.

Assuming that nuclear energy has to be sold on the wholesale market, we bet that it will be sold like a stream of "energy blocks".

Energy blocks are fixed quantities sold over a very short period of time at a price determined by the market at each period (then a "spot price"). The French market has periods of half an hour, which means 48 prices per day, 17520 prices per year. Such spot prices are very volatile from day to day, during the day and along the year at the same time (see Figure 1, Source :

Reuters EcoWin). These 17520 prices are essentially determined by three characteristics (hour, labour day in opposition to the end of the week or at holidays, monthly components). There is also a strong seasonal variation.

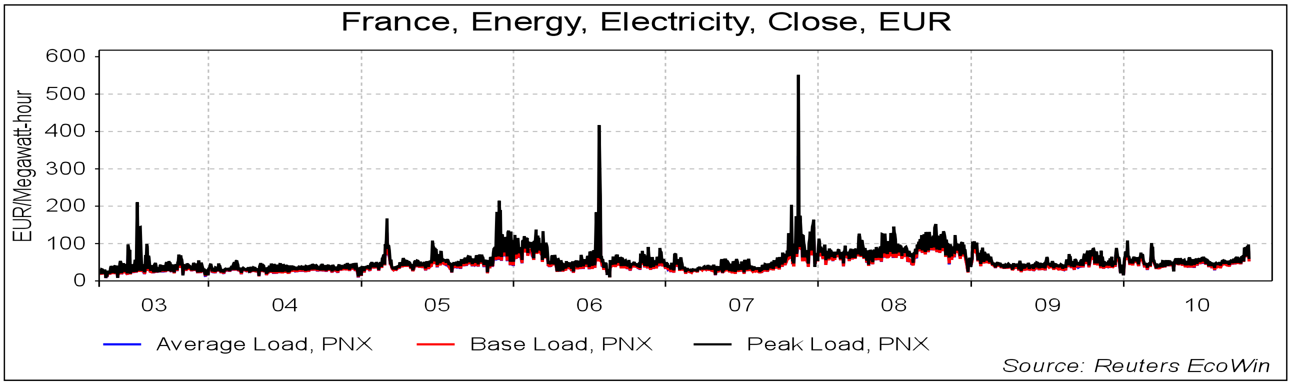

Figure 1: Spot prices on the French market.

Of course, the total value of the electricity produced during a campaign of nuclear fuel reservoir depends in a crucial way on the temporal profile of generation and how it can respond to the variation of demand and market price.

We can then benefit from an analogy with a hydro producer managing his reservoir and having to allocate the water of his basin between different periods of generation. To analyze the management of the reservoir of nuclear fuel, we can now draw from the important literature on the optimal management of hydro reservoir (see Ref. [1], [2]).

There are however differences between the nuclear plants and the hydro storage stations with respect to the characteristics of the "reservoir". An important point of differentiation is the timing of the reloading of the "reservoir". In the case of nuclear the reloading of the reservoir depends on the producer who is responsible for the optimal management of shut downs of the nuclear unit. While with the hydro reservoir only hazardous rain will do it when enough fallen. Another difference is that nuclear reloading stops production. Hydro reservoir stations do not stop during the reservoir's reloading while they cannot choose when and how much to reload (they have a very typical "seasonal reloading").

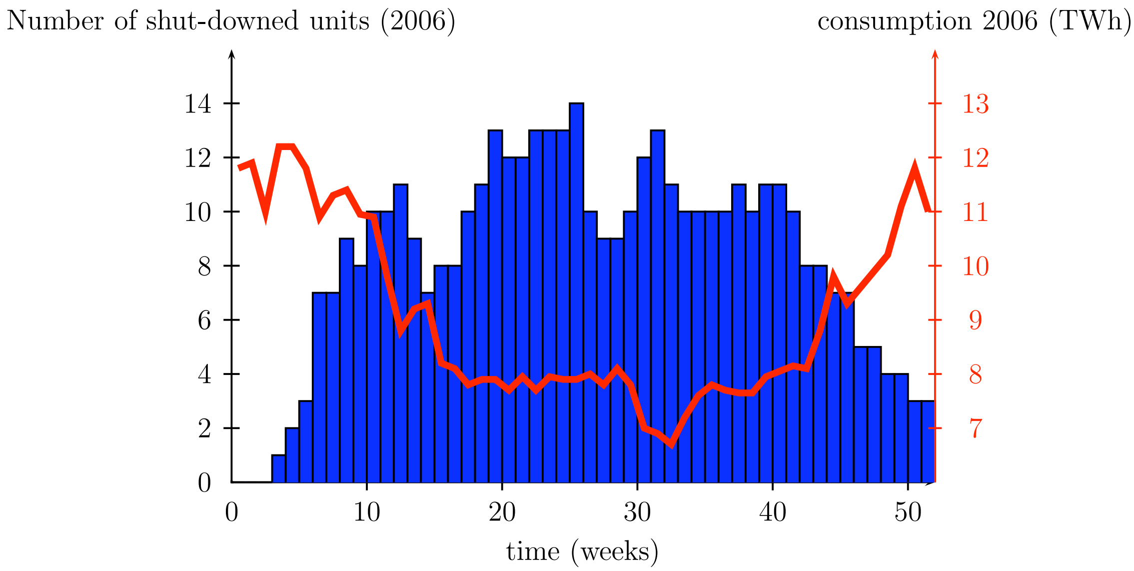

Figure 2: Availability of nuclear units.

However a seasonality of reloading has also to be considered in the nuclear case. A "good" seasonal allocation of the shut downs of nuclear plants consists in avoiding shut downs in winter (high demand) and concentrating them as much as possible between May and September (low demand) (see Figure 2, Source : EDF). Thus, the producer takes into account the level of demand when he chooses when to reload the heart of the reactor. A fundamental point of the optimization of the French nuclear set is therefore the allocation of the shut downs. Their timing and frequency are determining the length of the campaign for nuclear plants. In a market based electricity industry, the goal is here the maximization of the production's value.

Optimality and suboptimality of the nuclear set. A numerical example. It is usually thought that a flexible management of the generation of nuclear plants does not make sense. It is because, the nuclear plants are deemed to cover only the base load demand: operating in a constant way to their maximum capacity in order to recover their fixed costs on the biggest possible amount of energy generated. In a competitive market if the marginal technology[1] is nuclear all the year, the nuclear producers cannot cover the fixed costs. In such a market, the fixed costs and the variable costs will be covered let say on a yearly basis only if the nuclear set has its optimal size within the whole generation set (see Ref. [9]). Following the numerical example of Spector the optimal nuclear set for France corresponds to a nuclear marginality of 40%. This exactly means that nuclear plants can cover all their fixed-costs through existing continental Europe market-based prices during the 60% of marginality of the other thermal generation technologies (assuming that wind is not taken into account: basically coal, gas and fuel oil) on the basis of marginal costs of the latter.

However, the nuclear set could also be smaller than its optimal level. In this case, even in presence of perfect competition, it would be remunerated above its marginal costs more than 60% of time. Consequently, its holders would profit from a scarcity rent, whatever the intensity

[1] According to the merit order, which is a way of ranking the various available technologies of electricity generation, in the same order like their marginal costs of production, a combination of different generation technologies is made to reach the level of demand at a minimum cost. The price in the market is therefore determined by the marginal cost of the "last technology" used to equilibrate supply and demand (perfect competitive case). This technology is also called marginal technology.

of competition would be on the wholesale market. A variation of the scarcity rent can also occur if a sudden modification affects supply or demand (e. g. increase of the cost of fossil energies, increase of national or foreign demand), because the nuclear set cannot adjust instantaneously to such variations.

Spector estimates that vis-à-vis the current size of the continental European market the French nuclear set is "sub-dimensioned", which makes the owner of that set (the French state) recipient of a scarcity rent (see Ref. [10]).

3 Model: Perfect competitive case

In this section, we describe our general deterministic model of a perfectly competitive electricity market where the producers manage both nuclear and non-nuclear thermal plants. We assume a perfect competition according to which firms treat price as a parameter and not as a choice variable. Price taking firms guarantees that when firms maximize their profits (by choosing the quantity they wish to produce and the technology of generation to produce it with) the market price will be equal to marginal cost. The general frame is also characterized by perfect equilibrium between supply and demand and perfect information among producers. First, our modelling aims at determining the optimal management of the nuclear generation set in that competitive regime. More precisely we want to focus on the medium-term horizon which is characterized by the seasonal variation of demand between winter and summer. Second, they are the constraints imposed by generation capacity and fuel storage that play a central role to determine the equilibrium outcomes in this electricity market.

3.1 Modelling the demand

The demand, being exogenous, is considered perfectly inelastic. It is obviously a simplification. It can nevertheless be motivated by some arguments. In short-term to medium-term, the demand is less sensitive to price because it is already determined by previous investments in electrical devices and ways of life whose evolutions require time.

Electricity is sold to consumers[2] by retailing companies. There is no bilateral contracting regime between retailers and producers. The wholesale spot prices are paid by the retailers directly to the producers.

3.2 Modelling the time horizon

The time horizon of the model is T= 36 months[3] beginning by the month of December. A nuclear producer has two main options with respect to the scheduling of fuel reloading: (i) 1/3 of fuel reservoir that corresponds to 18 months of campaign and 396 days equivalent to full capacity for a unit of 1300 MW, (ii) 1/4 of fuel reservoir that corresponds to 12 months of campaign and 258 days equivalent to full capacity for a unit of 1500 MW. In order to get a tractable model, we need a cyclic model for the modelling of the campaign. Consequently, we retain this second mode of reloading and therefore a duration of campaign equivalent to 12 months in order to have a cyclic model with a periodicity of one year. The period of campaign is then decomposed into 11 months being the period of production and 1 month corresponding

[2]In fact in the French case, most of the consumers have a fixed price contract being a regulated price contract set by the government. This regulated price does not follow the wholesale market price evolution while a French "market-based" contract does every six or twelve months.

[3]The time horizon of the model is a multiplicative of twelve being expressed in months. Therefore it could be modified.

to the month of reloading of the fuel. We also assume that value is not discounted during the period of 36 months.

3.3 Modelling the generating units

We define 12 types of nuclear generating units while we also have 12 non-nuclear thermal generating units being all of a single type. A nuclear or a non-nuclear thermal producer can operate with several types of generating units. Since the non-nuclear thermal units are all of the same type, they will all act (hence produce) symmetrically. We assume that the nuclear units differ only by the available nuclear capacity that each of them holds and the month of their reloading. It means that all these nuclear units have the same cost function. We can then define our twelve "types" of nuclear units. Each type indexed by $j = 1, \cdots, 12$ corresponds to a different month of reloading of the nuclear unit. To be precise: a unit which belongs to the type of unit $j = 1$ (respectively $j = 2$, $\cdots$, $j = 12$) shuts-down the month of December (respectively January, $\cdots$, November).

The level of the nuclear production during the month $t = 1, \cdots, T$ for the unit j will be denoted by q_{jt}^{nuc}. Furthermore, the maximum nuclear production that can be realized by the unit j during a month is given by the parameter $Q_{max}^{j,nuc}$, while the minimum nuclear production is equal to $Q_{min}^{j,nuc}$. The variable S_t^j, which represents the quantity of fuel stored in the nuclear reservoir and available to the unit j at the beginning of the month t, is the potential energy that can be produced with this stock.

Symmetrically, the non-nuclear thermal units also have their own common capacity and cost function. The level of the non-nuclear thermal production during the month $t = 1, \cdots, T$ for the unit j will be denoted by q_{jt}^{th}. Furthermore the maximum non-nuclear thermal production that the unit j can do during a month is given by the parameter $Q_{max}^{j,th}$ and corresponds to the nominal non-nuclear thermal capacity, while there is no minimum for non-nuclear thermal production $Q_{min}^{j,th} = 0$.

3.4 Modelling the production costs

The nuclear cost function is made of a fixed part determined by the cost of investment, the fixed cost of exploitation and taxes and a variable part which corresponds to the variable cost of exploitation and the fuel cost. We assume that the cost function $C_j^{nuc}(.)$ of the nuclear production is linear and defined as

$$C_j^{nuc}(q_{jt}^{nuc}) = a_{nuc} + b_{nuc} q_{jt}^{nuc}.$$

The non-nuclear thermal cost function is also made of a fixed part which corresponds to the cost of investment, the fixed cost of exploitation and taxes and a variable part covering the variable cost of exploitation, the fuel cost, the cost of CO_2 as well as the taxes on the gas fuel. We assume that the non-nuclear production has a quadratic cost function $C_j^{th}(.)$ which is the following

$$C_j^{th}(q_{jt}^{th}) = a_{th} + b_{th} q_{jt}^{th} + c_{th} {q_{jt}^{th}}^2.$$

The nuclear and non-nuclear cost functions are monotone increasing and convex functions of q_{jt}^{nuc} and q_{jt}^{th} respectively. We choose a quadratic cost function in the case of non-nuclear thermal because of the increasing marginal cost of the non-nuclear production since it results from different fossil fuel generation technologies (e. g. coal, gas -combined cycle or not-, fuel oil). Furthermore, the non-nuclear production needed a non constant function in order to recover its fixed costs. So, we assume that the marginal cost of nuclear is a constant function of q_{jt}^{nuc} while that of the non-nuclear thermal is an increasing function of q_{jt}^{th}.

3.5 Modelling the nuclear fuel stock

Let us denote S^j_{reload}, the nuclear fuel stock of reloading available to the unit j. The evolution of the nuclear fuel stock is then determined by the following rules

$$S^j_1 \text{ given, } S^j_{t+1} = \begin{cases} S^j_t - q^{nuc}_{jt}, & \text{if no reload during month } t \text{ for unit } j \\ S^j_{reload}, & \text{if unit } j \text{ reloads during month } t \end{cases} \tag{1}$$

The relationship 1 traces the evolution of the stock given the flow of the nuclear production. In the case that t is the month during which the producer reloads the fuel of the reactor, the stock at the beginning of the following month (beginning of the campaign) is equal to S^j_{reload}. Moreover, we impose

$$S^j_{T+1} \geqslant S^j_1 \tag{2}$$

The constraint 2 implies that the producer must keep his nuclear units at the end of the game in the same storage condition as the initial one. It means that each nuclear producer has to finish the period T at least with the same quantity of nuclear fuel as the initial one. In this way each producer has to "spare" his nuclear fuel during the production period. Such a constraint is implicit if the end of period T coincides with the end of the campaign. In the case of virtual plants[4] the constraint 2 has to be imposed together with a system of penalty.

3.6 A "naive" modelling of the optimal production behavior

If the unit j holds at time t the stock S^j_t, then it could try to solve the following optimal production problem

$$\max_{q^{nuc}_{jt}, q^{th}_{jt}} p_t \cdot (q^{nuc}_{jt} + q^{th}_{jt}) - C^{nuc}_j(q^{nuc}_{jt}) - C^{th}_j(q^{th}_{jt})$$

subject to the constraints

$$\begin{cases} Q^{j,nuc}_{min} \leqslant q^{nuc}_{jt} \leqslant Q^{j,nuc}_{max}, & \text{if no reload during month } t \text{ for unit } j \\ q^{nuc}_{jt} = 0, & \text{if unit } j \text{ reloads during month } t \end{cases} \tag{3}$$

$$0 \leqslant q^{th}_{jt} \leqslant Q^{j,th}_{max} \tag{4}$$

where the price p_t is given (perfect competition) by the equality between supply and demand.

The constraint 3 shows that the nuclear production of each month is bounded by the minimum/maximum quantity of nuclear production which can be obtained during a month. The non-nuclear thermal production is a non negative quantity which is also bounded by the maximum non-nuclear thermal production (constraint 4). The producer may use the non-nuclear thermal resources to produce electricity until he reaches the level of demand of the corresponding month while respecting at the same time the constraint 4.

The solution of this problem determines the new level of stock S^j_{t+1}. Unfortunately, such a process does not take sufficiently into account the constraints of the stock. In particular, one may face an insufficient level of stock in order to produce $Q^{j,nuc}_{min}$ every month.

[4]The operator of the electricity generation set provides access to a number of MW of generation capacity that can be obtained by producers, suppliers and traders through an auction mechanism. He sells this production capacity in the form of energy purchase contracts. The buyers of these contracts, have drawing rights on the set, at a predetermined proportional cost, without incurring all the technical and the operational risks inherent in the physical properties of plants. Hence the name of VPP - Virtual Power Plant - given to the sold products. Ones meet VPP auctions in several European countries (e. g. France, Belgium, Netherlands, Denmark, Germany, etc...)

3.7 Alternative constraint of the nuclear fuel stock

In order to introduce all the "auxiliary variables" of the nuclear fuel stock S_t^j in the optimization problem, let us first remark that there exist implicit conditions. Let us consider for example that the unit j at month t has 3 months of campaign that remain until the month of reloading (including the month t), then the constraints 1 and 3 imply the following condition:

$$S_t^j \geqslant 3 \cdot Q_{min}^{j,nuc}$$

This inequality results from the comparison between the current level of stock and the quantity $3 \cdot Q_{min}^{j,nuc}$ which is equivalent to the total quantity of nuclear fuel that the unit j has to keep in order to realize the minimum nuclear production at each of the remaining months until the end of the campaign. In addition, one has to take into account the final constraint (constraint 2). Let us introduce by backward induction the variable $S_{t,min}^j$ which is the quantity of nuclear fuel that the unit j has to reserve at the beginning of the month t in order to "finish" the campaign; that is to produce at least $Q_{min}^{j,t+1,nuc}$ during the month $t+1$, $Q_{min}^{j,t+2,nuc}$ during the month $t+2$, $\cdots$ until one reaches either the month of reloading or the end of the game.

The notation $Q_{min}^{j,t,nuc}$ represents the minimum nuclear production realized by the unit j during period t. Let us notice that during the month of reloading the minimum nuclear production provided by the unit j is zero. Otherwise, $Q_{min}^{j,t,nuc}$ equals to the minimum nuclear production $Q_{min}^{j,nuc}$ that can be realized during a month. More precisely,

$$Q_{min}^{j,t,nuc} = \begin{cases} Q_{min}^{j,nuc}, & \text{if no reload during month } t \text{ for unit } j \\ 0, & \text{if unit } j \text{ reloads during month } t \end{cases}$$

We define $S_{t,min}^j$ as following

$$\text{for } t < T,\ S_{t-1,min}^j = \begin{cases} 0, & \text{if unit } j \text{ reloads during month } t \\ 0, & \text{if month } t \text{ is the last month of campaign for unit } j \\ S_t^j + Q_{min}^{j,t,nuc}, & \text{in other cases} \end{cases}$$

$$\text{for } t = T,\ S_{T,min}^j = \begin{cases} S_1^j, & \text{if no reload during month } T \text{ for unit } j \\ 0, & \text{if unit } j \text{ reloads during month } T \end{cases}$$

It is important to mention that the maximum nuclear production that the unit j is able to provide during the month t depends on the level of stock at the beginning of the month t. In particular, if the stock is close to zero, then the maximum nuclear production will be close to zero.

We define $Q_{max}^{j,t,nuc}$ as the maximum nuclear production that can be realized by the unit j during the month t. We remark that $Q_{max}^{j,t,nuc}$ is equal to the minimum between the remaining stock (quantity of stock available to the unit j at the beginning of the month t minus the reserve) which is available at the beginning of t and the maximum nuclear production that can be realized during a month. However, if t is the month of reloading then $Q_{max}^{j,t,nuc}$ is equal to zero.

$$Q_{max}^{j,t,nuc}(S_t^j) = \begin{cases} \min(S_t^j - S_{t,min}^j, Q_{max}^{j,nuc}), & \text{if no reload during month } t \text{ for unit } j \\ 0, & \text{if unit } j \text{ reloads during month } t \end{cases}$$

Later, we will use the reduced notation $Q_{max}^{j,t,nuc}$ for the variable $Q_{max}^{j,t,nuc}(S_t^j)$. This notation is not ambiguous since the problem will be solved recursively; firstly one computes the solution for $t = 1$, which allows to determine the level of stock S_1^j, then we can solve the problem for $t = 2$, etc...

So, the constraint 3 of our optimization problem will take the reduced form

$$\begin{cases} Q_{min}^{j,t,nuc} \leqslant q_{jt}^{nuc} \leqslant Q_{max}^{j,t,nuc}, & \text{if no reload during month } t \text{ for unit } j \\ q_{jt}^{nuc} = 0, & \text{if unit } j \text{ reloads during month } t \end{cases}$$

3.8 Decentralization rules

The comparison between the aggregate maximum nuclear production that can be realized each month by the different units and the corresponding demand determines the perfect competitive price as well as the optimal levels of nuclear and non-nuclear thermal productions. Note that the monthly demand which is considered in this model results from the difference between the level of demand $D(t)$ observed at the month t and the aggregate hydro production $Q_{Tot}^{t,hyd}$ provided during the month t. Let us also remark that since the hydro technology with no reservoir (run-of-river) is a base load generation technology which is presumably never marginal, it is necessary to call up nuclear to cover the different levels of demand.

At each date t, the price p_t is determined by the equality between supply and demand:

$$\sum_{j=1}^{12} q_{jt}^{nuc}(p_t) + \sum_{j=1}^{12} q_{jt}^{th}(p_t) + Q_{Tot}^{t,hyd} = D(t),$$

where $(q_{jt}^{nuc}(p_t), q_{jt}^{th}(p_t))$ is the solution of the optimization problem involving the parameter p_t. Note that this condition is not correctly written since the solution is not necessarily unique, the nuclear production is not a function of the price but a correspondence. This is why we will distinguish the two following rules.

3.8.1 Decentralization rule when nuclear is marginal

If the demand at the month t, $D(t) - Q_{Tot}^{t,hyd}$, is inferior or equal to the corresponding aggregate maximum nuclear production available at the date t, then the nuclear is the "last technology" used to equilibrate supply and demand (i. e. the marginal technology) and according to the "merit order" the price is determined by the marginal cost of nuclear production which is (roughly) constant. In this case, the non-nuclear thermal production is zero and the total nuclear production is allocated between the j units to respect the constraints of our optimization problem and a rule of "equal treatment". This rule guaranties that the offer is equal to the demand, all constraints are satisfied and the ratio of use of the "mobilizable capacities" $(Q_{max}^{j,t,nuc} - Q_{min}^{j,t,nuc})$ is the same. The level of the nuclear and non-nuclear thermal production is determined respectively as

$$q_{jt}^{nuc} = Q_{min}^{j,t,nuc} + (Q_{max}^{j,t,nuc} - Q_{min}^{j,t,nuc}) \frac{D(t) - Q_{Tot}^{t,hyd} - \sum_{j'=1}^{12} Q_{min}^{j',t,nuc}}{\sum_{j'=1}^{12} Q_{max}^{j',t,nuc} - \sum_{j'=1}^{12} Q_{min}^{j',t,nuc}}, \text{ for all } j$$

and

$$q_{jt}^{th} = 0, \text{ for all } j,$$

The value of the perfect competitive price is

$$p_t = b_{nuc}.$$

3.8.2 Decentralization rule when non-nuclear thermal is marginal

If the aggregate maximum nuclear production is not sufficient to cover the demand $D(t)-Q_{Tot}^{t,hyd}$ during the month t, producers use non-nuclear thermal resources to generate electricity in order to reach the level of demand at t. Then the non-nuclear thermal generation technology is the marginal one and according to the "merit order" the perfect competitive price is given by the marginal cost of the non-nuclear thermal production which is a linear increasing function of the non-nuclear thermal production q_{jt}^{th}. In this case, each nuclear unit j produces to the maximum of its available capacity $Q_{max}^{j,t,nuc}$ and each non-nuclear thermal unit produces symmetrically in order to cover the "residual demand" (demand $D(t)-Q_{Tot}^{t,hyd}$ at month t minus the aggregate maximum nuclear production at month t) which corresponds to it. Consequently, the quantity of nuclear and non-nuclear thermal production is respectively

$$q_{jt}^{nuc} = Q_{max}^{j,t,nuc}, \text{ for all } j$$

and

$$q_{jt}^{th} = \frac{D(t) - Q_{Tot}^{t,hyd} - \sum_{j'=1}^{12} Q_{max}^{j',t,nuc}}{12}, \text{ for all } j.$$

The perfect competitive price is defined as

$$p_t = b_{th} + 2c_{th}q_{jt}^{th}.$$

3.8.3 Decentralization rule when non-nuclear thermal is marginal

If the aggregate maximum nuclear production is not sufficient to cover the demand $D(t)-Q_{Tot}^{t,hyd}$ during the month t, producers use non-nuclear thermal resources to generate electricity in order to reach the level of demand at t. Then the non-nuclear thermal generation technology is the marginal one and according to the "merit order" the perfect competitive price is given by the marginal cost of the non-nuclear thermal production which is a linear increasing function of the non-nuclear thermal production q_{jt}^{th}. In this case, each nuclear unit j produces to the maximum of its available capacity $Q_{max}^{j,t,nuc}$ and each non-nuclear thermal unit produces symmetrically in order to cover the "residual demand" (demand $D(t)-Q_{Tot}^{t,hyd}$ at month t minus the aggregate maximum nuclear production at month t) which corresponds to it. Consequently, the quantity of nuclear and non-nuclear thermal production is respectively

$$q_{jt}^{nuc} = Q_{max}^{j,t,nuc}, \text{ for all } j$$

and

$$q_{jt}^{th} = \frac{D(t) - Q_{Tot}^{t,hyd} - \sum_{j'=1}^{12} Q_{max}^{j',t,nuc}}{12}, \text{ for all } j.$$

The perfect competitive price is defined as

$$p_t = b_{th} + 2c_{th}q_{jt}^{th}.$$

3.9 Nuclear production programming

According to the modelling of the optimal production behavior introduced in subsection 3.7, the production programme resulting from the decentralization rules is unfeasible because of the violation of production constraints. In particular, we observe the violation of the maximum non-nuclear thermal production constraint. In fact the non-nuclear thermal production is insufficient since it is not able to cover the demand especially during the last months of period T.

Therefore, the nuclear set has to be managed so that the equality between supply and demand is respected over the whole period.

For this reason, we provide a second scenario less myopic in which we propose a programming of the nuclear production in order to obtain a feasible production which satisfies the following condition:

(i) It respects the minimum/maximum production constraints as well as the constraints of the nuclear fuel stock. In particular, it guarantees that the maximum non-nuclear thermal production (coal, gas, fuel, etc...) will not be exceeded by the monthly demand. It implies that the programmed nuclear production is superior or equal to the monthly demand minus the maximum non-nuclear thermal production

$$\sum_{j=1}^{12} q_{jt}^{plan} \geqslant D(t) - Q_{Tot}^{t,hyd} - Q_{max}^{t,th}, \text{ for all } t.$$

Our algorithm determines a variable $(q_{j,t}^{plan})$ satisfying (i). The variable $q_{j,t}^{plan}$, computed by backward induction, tries to treat symmetrically the units (same level of activity). However, we also have to take into account the current disparities between the units (level of nuclear fuel stock, being or not close to the time of reloading, etc...)

Note that there are several solutions which satisfy the condition (i). It should be also mentioned that the optimality of such feasible solutions is based on the merit order dispatch (cf. Footnote 1 page 6).

4 Data

The data used in our numerical dynamic model is French and of different years due to the difficulty of collection: $*$ level of French demand during the year $2006-2007$, $*$ fixed and variable costs of nuclear, coal and gas generation, $*$ generation capacity of hydro (run-of-river), nuclear and non-nuclear thermal and $*$ nuclear fuel stock of reloading. The consumption comes from the French Transmission & System Operator (named RTE). It gives the daily consumption in MWh for the month of December 2006 and the entire year 2007 with which we determine the monthly consumption. RTE also provides the annual capacity of nuclear as well as the annual capacity of gas and coal for the year 2009. In addition, the nuclear fuel stock of reloading as well as the annual capacity and production of hydro have been provided by (Electricité de France).

The costs of production come from the official report "Reference Costs of Electricity Production" issued by the ministry of industry (General Direction of Energy and Raw Materials -DIDEME-) (See Ref. [17]) in 2003. This report gives the technical characteristics, the costs, and a sensitivity analysis for different types of generation technologies (nuclear, coal, gas, fuel). It also gives the life duration, the availability of the generating units as well as the typical management of the fuel for nuclear. These data are calculated for the year 2007 and 2015. The report also gives the cost of investment, the variable / fixed cost of operation, the cost of fuel as well as the external costs (e. g. cost of CO_2, cost of a major nuclear accident, etc...). It also provides the total cost of production for a base load (8760h) and semi-base (3000h) operation.

It gives the total cost for each technology as follows: cost of investment, variable and fixed cost of exploitation, fuel cost, taxes, $R\&D$ costs for the nuclear and cost of CO_2 per ton in the case of coal and gas for the same levels of operation that previously mentioned. These costs are estimated for the year 2007 and 2015 with different discount rate (3%, 5%, 8%, 11%) taking into account the influence of exchange rate on the production cost. Finally, a sensitivity analysis links production costs to the main parameters for each technology (e. g. investment cost, availability, life duration, etc...).

We know that the level of the fixed and variable costs depends crucially on the discount rate. For example, the investment cost for nuclear is set at 6,4 Euros/MWh with a discount rate at 3% and at 16,3 Euros/MWh for a discount rate of 8%. To end: the life duration retained for the non-nuclear thermal units is 30 years, while the new reactor EPR (European Pressurized Reactor) is conceived to operate for 60 years.

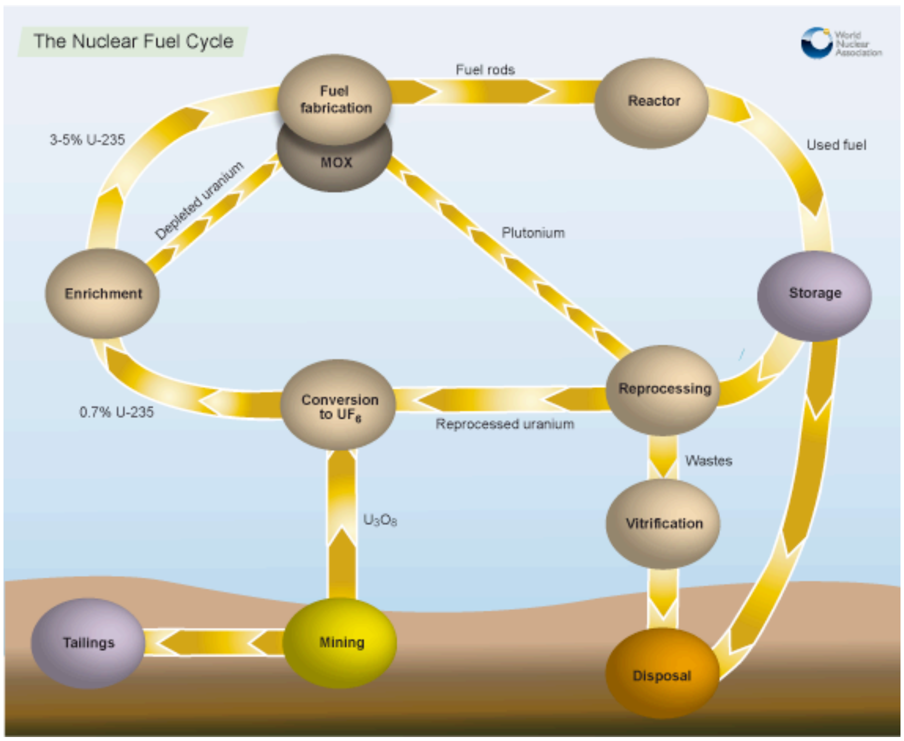

Figure 3: Nuclear fuel cycle.

In addition to all this, the nuclear fuel (being "enriched uranium") has its own distinctive fuel cycle deeply different than other resources such as coal, oil and natural gas. Nuclear fuel is processed through several steps like: mining and milling, conversion, enrichment, and fuel manufacturing (see Figure 3, Source : World Nuclear Association). The resulting duration of the nuclear fuel cycle is significantly high. Finally, a last main characteristic of nuclear is the storage of waste and the long process of the dismantling of plants (Source: Brite/Euram III: Projects). Therefore, the discount rate is a very critical factor which can significantly affect the nuclear costs.

Moreover, the cost of non-nuclear thermal production is itself highly volatile for different reasons. One is the price volatility of CO_2. The CO_2 futures prices for 2007 delivery ranged between almost 0 and 30 euros per ton of CO_2 during just the twelve month period May 2006 - May 2007 in Phase I of the EU ETS (Source: The Brattle Group, Cambridge).

The other considerable volatility factor has been the sharp move of oil prices (and gas prices)

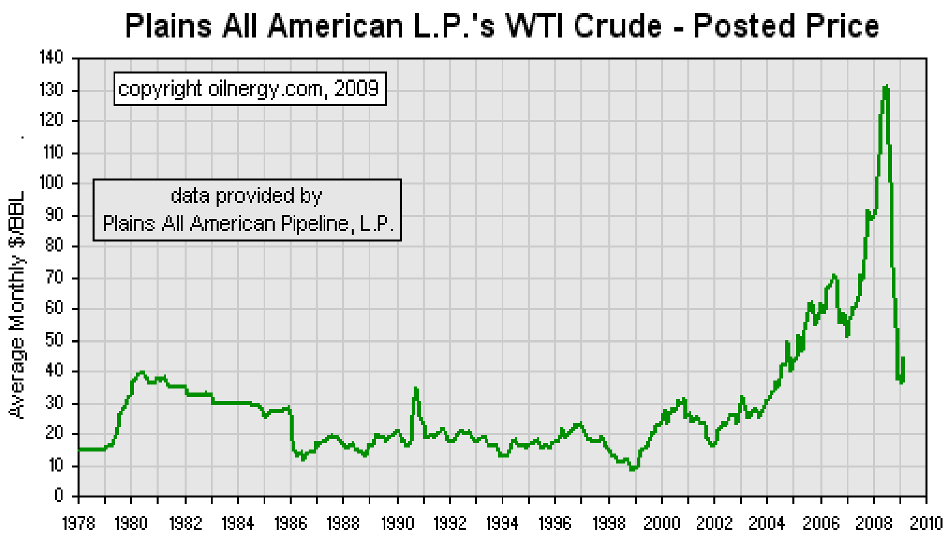

Figure 4: Average monthly data from January 1978 through March 2009.

these last years (see Figure 4, Source: Oilnergy).

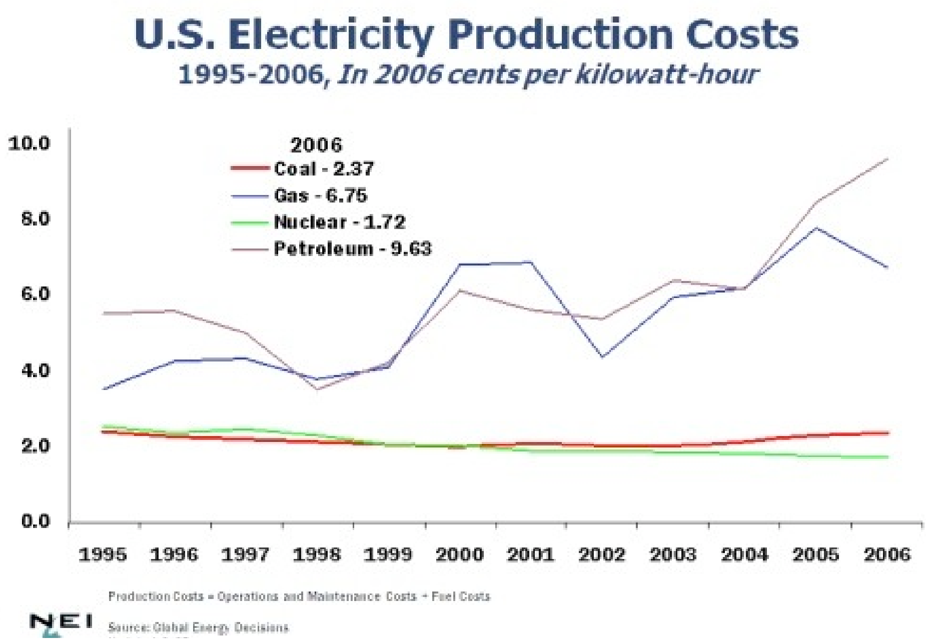

Figure 5: Evolution of electricity production costs.

On the contrary, the cost of nuclear fuel and the operation costs[5] are less volatile during that period than the costs of non-nuclear thermal production (see Figure 5, Source: World Nuclear Association, Global Energy Decisions). This is due mainly to two reasons; firstly the small level of uranium cost as component of the final fuel cost, second a stabilization factor resulting of the delay between the extraction of natural uranium and the final manufacturing of nuclear fuel.

[5]The above data refers to fuel plus operation and maintenance costs only, they exclude capital costs, since these vary greatly among utilities and states, as well as with the age of the plant.

Our modelling is based on a scenario in which one dollar is equal to one euro, the discount rate is 8%, the cost of CO_2 per ton reaches the 20 euros, the price of coal is 30 dollars per ton and the price of gas is 3.3 dollars per MBtu (1 MBtu=293.1 KWh). In addition, the value of the coefficient a_{th} involved in the non-nuclear thermal cost function corresponds to the fixed cost provided by the data (investment cost, fixed exploitation cost), while the other coefficients have been determined by interpolation in order to meet the variable cost of coal and gas provided by our data base (fuel cost, variable exploitation cost, CO_2 cost, taxes). The capacity of each nuclear unit has been simulated[6] in order to approximate the graph of figure 2, which shows the availability of nuclear units per week. Moreover, the initial value of the nuclear fuel stock has been set by simulating the nuclear fuel stock of each unit available at the beginning of the time horizon of the model. We also take into account the electricity losses of the network, as estimated by RTE.

5 Numerical Illustration

We study the nuclear and non-nuclear thermal production decisions as well as the storage decisions analyzed in the previous section, within a simple numerical model.

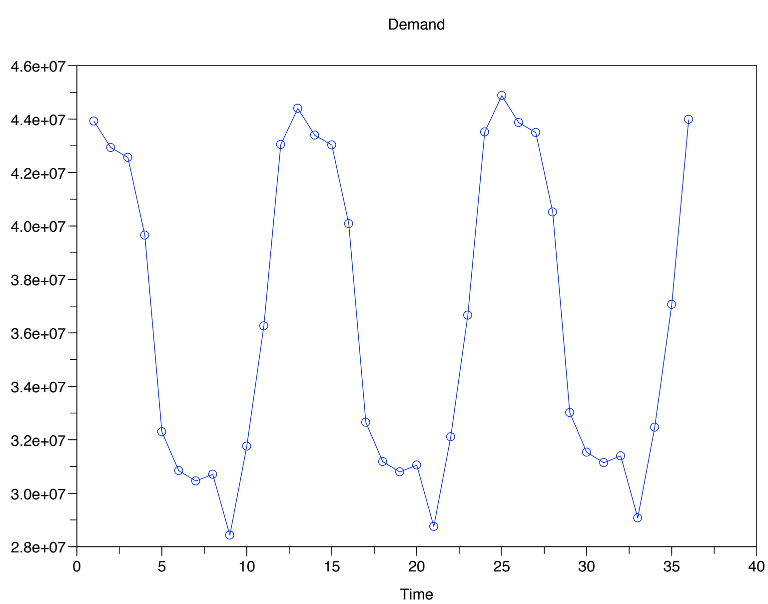

Figure 6: Simulated demand (in MWh)

The levels of monthly demand[7] obtained with the time scale of our model (December 2006 – November 2009) are presented in the figure 7 (we suppose an exponential augmentation of the demand by using a rate of 1% per year). One can see the seasonal variation of the demand level between winter (high demand) and summer (low demand). One observes a high level of demand during November, December, January and February with demand peaks in December. The demand falls during spring as well as during summer (May – August). On the contrary,

[6]Access to nuclear capacity data is not possible due to the confidentiality of such data.

[7]Note that there is a rescalling on this data in order to take into account the diversity on the length of the months.

one does not observe any demand peaks during summer period which implies that there were no significant extremes of temperature.

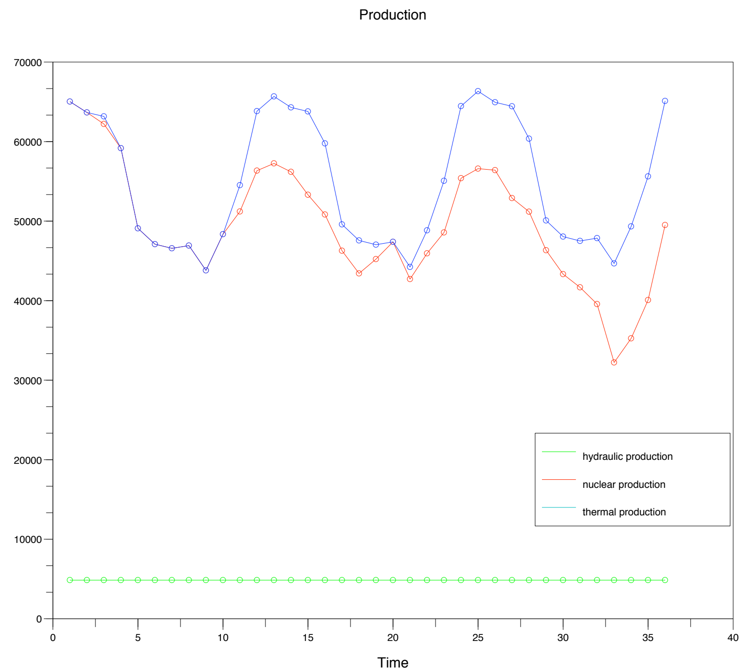

Figure 7: Simulated hydro/nuclear/non-nuclear thermal production (in MW)

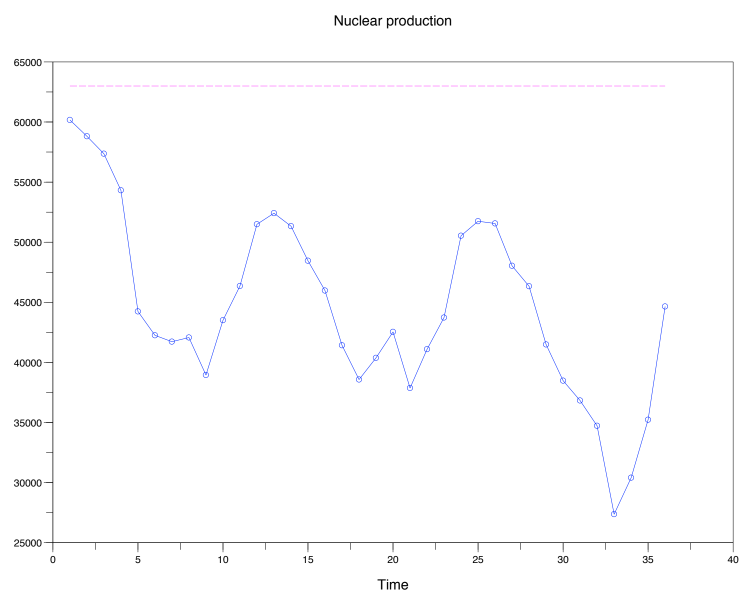

Figure 8: Simulated nuclear production (in MW)

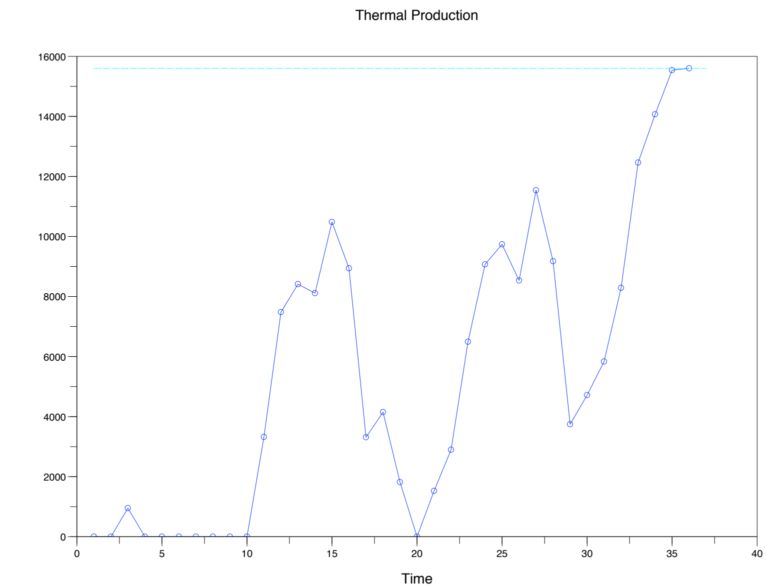

Figure 9: Simulated non-nuclear thermal production (in MW)

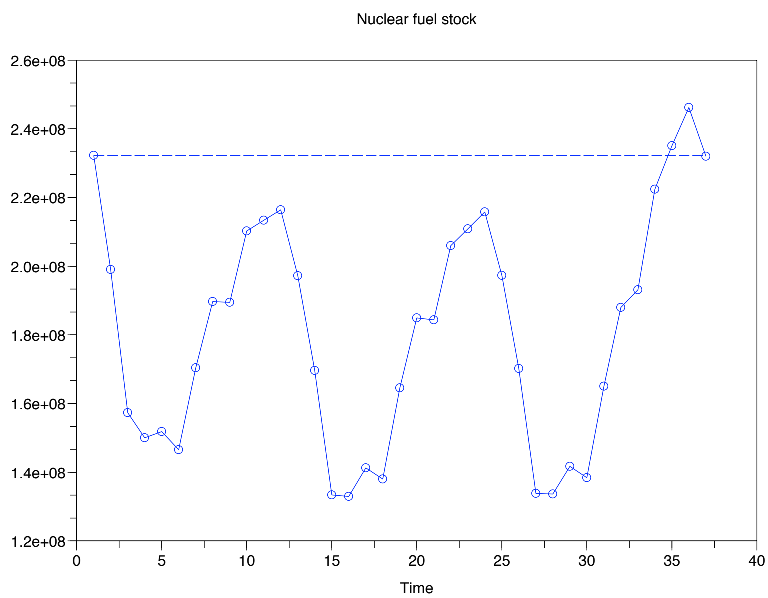

Figure 10: Simulated nuclear fuel stock (in MWh)

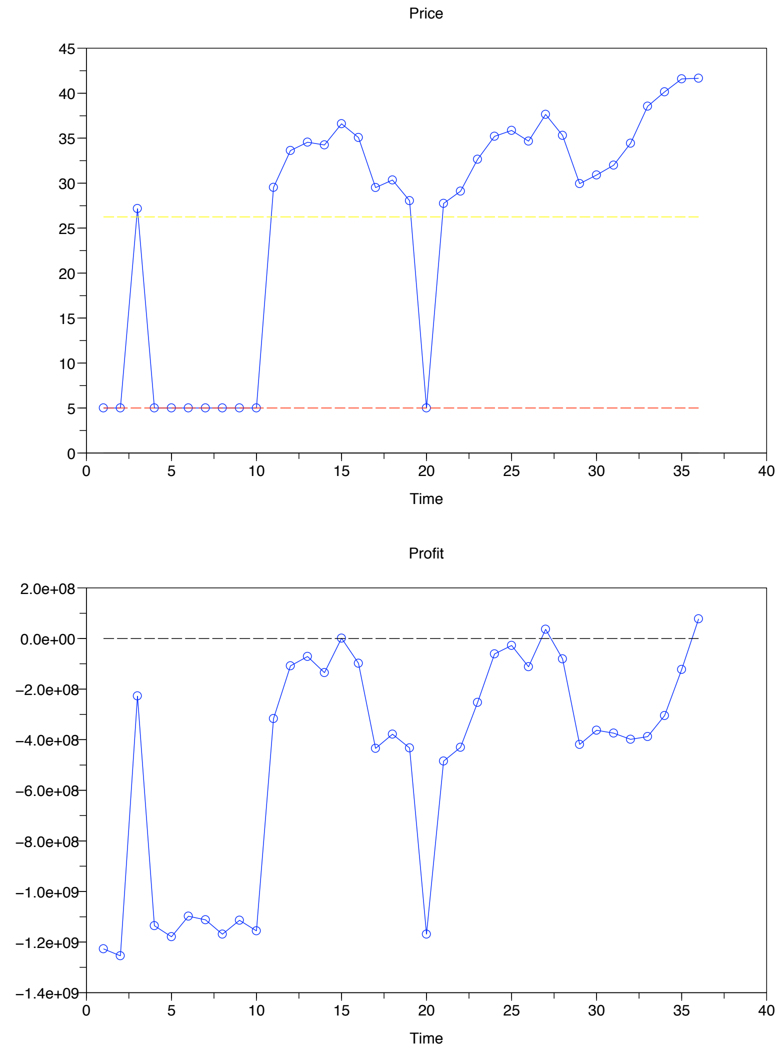

Figure 11: Simulated price (in Euro/MWh)/Aggregated total profit (in Euro)

General simulation results

The non-nuclear thermal generation is marginal during most of the months of period T in order to equilibrate supply and demand while the nuclear technology is marginal only at the beginning of period T. Nuclear stays marginal during almost the entire period of winter, spring and summer of 2007. In addition, nuclear follows the seasonal variations of the demand by decreasing during summer and increasing during winter.

Furthermore, one observes that the monthly nuclear production never reaches its maximum value (see Figure 7, Figure 8, Figure 9). However the reader should not focus on the precise amount of profit since its level depends on the too many approximations we did do (euro/dollar, oil prices, CO_2 cost, discounting rate, etc...) and because our modelling does not take into account the electricity importations/exportations or the production coming from renewable (see Figure 11).

We separate period T into three sub-periods according to the evolution of both nuclear and non-nuclear thermal productions. According to Figure 7, we distinguish a first sub-period during which nuclear is mainly the marginal technology, a medium sub-period with a periodical evolution of the nuclear and non-nuclear thermal production and, finally, a third sub-period.

First sub-period

The total nuclear production approaches its maximum level during the first months of the simulation (December 2006, January 2007) corresponding to the "over-consumption" of the nuclear fuel stock. On the contrary, the non-nuclear thermal production is equal to zero during the first months of period T (with the only exception of February) since the demand is covered by the nuclear production (see Figure 7, Figure 8, Figure 9, Figure 10). The price[8] reaches its lowest at the beginning of period T because of the marginality of the nuclear production. The only exception is the month of February 2007 during which the non-nuclear thermal technology becomes marginal. However, the price during this month is significantly lower than the price during the same month of the following years because of the importance of nuclear production at the beginning of period T which leads to a less important non-nuclear thermal production compared to that realized in February in the other years.

Note that if nuclear fuel stock is "overused" at the beginning of the time horizon of the model, significant losses[9] are generated (see Figure 11).

Medium sub-period

The nuclear production follows the seasonal variations of the demand (high production during winter – low production during summer) which means " high " levels of nuclear fuel stock during summer and "low" levels of nuclear fuel stock during winter. Therefore, the periodical evolution of the nuclear production implies a periodical evolution for the nuclear fuel stock too. Note that the trend of the stock appears significantly below the "stock of reference"[10] (see Figure 8, Figure 10).

Moreover, one observes that the non-nuclear thermal and the nuclear production increase (respectively decrease) simultaneously during almost the entire time horizon of our model, which corresponds to the notion of comonotonicity introduced by Yaari (1987) (see Figure 7). In addition, one can see that the non-nuclear thermal production is high during winter (respectively low during summer) because of the high (respectively low) level of demand. In particular, non-nuclear thermal production is increasing during winter (beginning from October) until it reaches its peak value during the month of December and February. Afterwards, non-nuclear thermal production decreases because summer period is a low demand season. However, non-nuclear stays marginal during summer because of the very low levels of the nuclear production (see Figure 9). Consequently, price is high during the months of winter by taking its highest value during the month of December and February and relatively low during summer. The aggregate profit obtained by the producer is high during winter and at the beginning of spring of 2008, 2009 while lower profits are realized during summer (see Figure 11).

Last sub-period

The total nuclear production is significantly low during the four last months of period T (August, September, October, November) which allows the refueling of the nuclear stock so that the producer gets his nuclear units at the end of the game with the same stock as the initial one (see Figure 8, Figure 10). On the contrary, the non-nuclear thermal units increase significantly their production during these months in order to cover the increased levels of demand because of the important decrease of the nuclear production. In particular, non-nuclear thermal production reaches its maximum value during the last two months of the model's time horizon (see Figure 7, Figure 9). For this reason, the price and the production profit reach their highest levels during this period (see Figure 11).

It should be noticed that, on this time scale, we do not meet Spector's conclusion about the

[8]The red (respectively yellow) dotted line indicates the price level when nuclear (respectively non-nuclear thermal) is the marginal technology.

[9]Note that mark-up rate is taken equal to zero.

[10]The "stock of reference" is represented by the blue dotted line which shows the value of stock at the beginning that is also the value of stock at the end.

insufficient size of the French nuclear set. In our exercise, it does not seem to be significantly below the "optimal size". A discretization of the time frame has been obtained by using weeks instead of months while it leads to the same conclusion (see Figure 12).

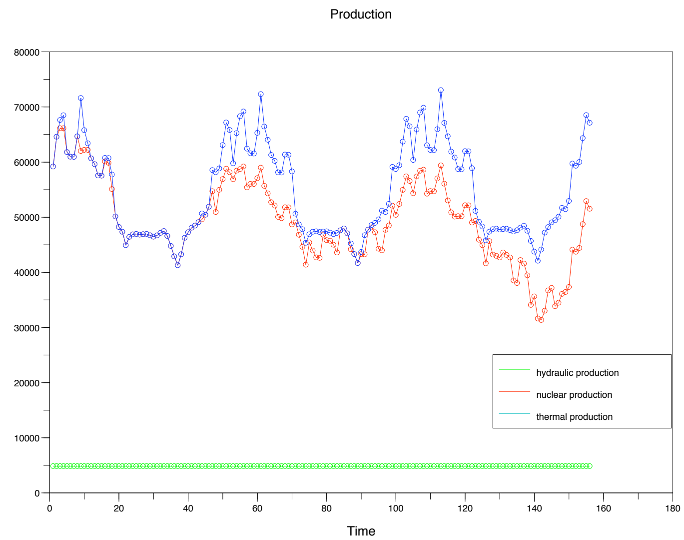

Figure 12: Simulated weekly hydro/nuclear/non-nuclear thermal production (in MW)

Note also that if $T \geqslant 36$ months, then producer's behavior does not change since the evolution of the nuclear and non-nuclear thermal production during the first and the last sub-period as well as the periodical evolution of the production during the medium sub-period is the same (e. g. for $T = 84$, see Figure 13).

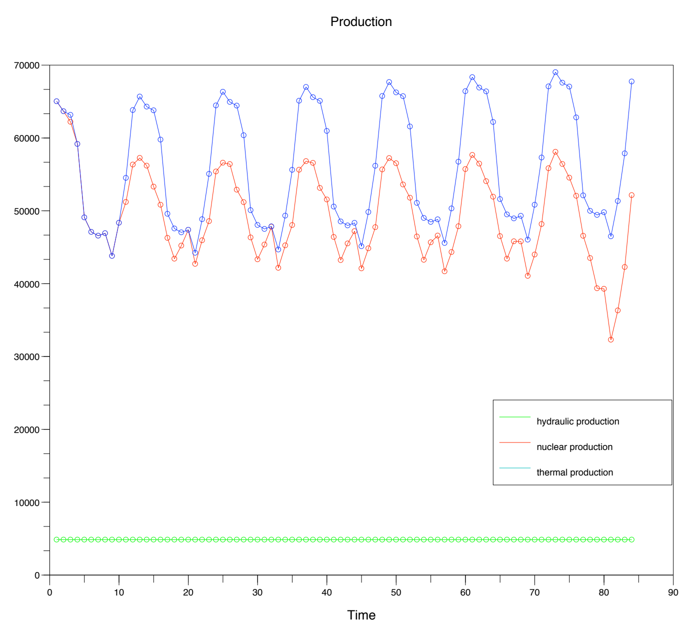

Figure 13: Simulated hydro/nuclear/non-nuclear thermal production (in MW)

6 Conclusion

In this paper, we did examine the optimal management of a flexible nuclear generation set in a perfectly competitive regime. We focussed on a "medium-term approach" which takes into account the seasonal variation of the demand between winter (high demand) and summer (low demand). The novelty of our paper consists in the fact that the nuclear fuel functions like a "reservoir", which allows different allocations of the nuclear production during the different seasons of the year. We did describe the characteristic of the nuclear fuel as "reservoir" and we did give a numerical simulation by taking into account the actual size of a given nuclear set (the French) vis-à-vis the non-nuclear generation set. We did propose a deterministic multi-period model to study the perfect competitive case in a market where producers use both nuclear and non-nuclear generations units. Then, we did propose "decentralization rules" while considering operational constraints related to the levels of nuclear production, of non-nuclear thermal production and of nuclear fuel stock. The efficient production levels (nuclear, non-nuclear thermal) as well as the price resulting from these rules given the nuclear production programming, depend on which generation technology is marginal during the observation period.

Three different approaches of nuclear programming have been distinguished. In a first approach, the nuclear is used to cover the base load demand by functioning always at its maximum capacity. This is typically not the French case where nuclear is used to meet both the base load and the semi-base (see Ref. [16]). In a second approach, we studied an alternative modelling of the nuclear generation. However in this early step, the minimum/maximum production constraints are not respected. We then provided a different scenario (being the third approach) in which the programming of the nuclear production respect the generation adequacy constraints.

In this late frame, we did find high levels of nuclear generation during the months of high demand (winter) and low levels during the months of low demand (summer), which confirms that nuclear can be a load-following generation technology. As expected, the evolution of the nuclear fuel stock is the opposite of the evolution of the nuclear generation (low levels of stock during winter – high levels of stock during summer). In addition, we notice that the different values of the nuclear fuel stock obtained during period T remain significantly lower than the "reference" value of this fuel stock. Furthermore, the producers increase their non-nuclear thermal production during winter and they decrease it during summer, according to the corresponding demand level and to the level of the nuclear generation. Nevertheless, non-nuclear thermal technology remains marginal during both seasons in the medium and last sub-period of time horizon T. Consequently, the price is determined by its marginal cost most of the time except at the beginning of period T. In particular, we did observe that market price peaks during winter and reaches its lowest during summer. Accordingly, producers obtain higher profits during winter and lower profits during summer.

We did model the optimal production behavior as an optimization per month production problem, which consists in the maximization of the production value during a month given the production of the previous month. However, this mode of operation could be qualified as "myopic" because it is not based on the optimization of the production over the entire period of the campaign. An inter-temporal optimization should result from the maximization of the value of generation during the whole length of the campaign (11 months) and it should lead to determine the global optimum of the optimal production problem. This further analysis is to be our next work.

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